ARO 15532.4-EG

FINAL TECHNICAL REPORT

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AD A136447

ACOUSTIC SIGNATURE FROM FLAMES AS A COMBUSTION DIAGNOSTIC TOOL

By

Warren C. Strahle

Prepared for

U.S. ARMY RESEARCH OFFICE
ENGINEERING DIVISION
RESEARCH TRIANGLE PARK, NC

November 1983

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ATLANTA, GEORGIA 30332

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Final Technical Report

Contract DAAG-29-79-C-0087

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A136447	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Acoustic Signature from Flames as a Combustion Diagnostic Tool		5. TYPE OF REPORT & PERIOD COVERED Final Report 5/1/79 - 10/31/83
		6. PERFORMING ORG. REPORT NUMBER None
7. AUTHOR(s) Warren C. Strahle		8. CONTRACT OR GRANT NUMBER(s) DAAG-29-79-C-0087
9. PERFORMING ORGANIZATION NAME AND ADDRESS School of Aerospace Engineering Georgia Institute of Technology Atlanta, GA 30332		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Research Officer Research Triangle Park, NC		12. REPORT DATE November 1983
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Distribution of this document is unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Acoustics, Combustion, Combustion Diagnostics, Gas Turbine

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A program was conducted to investigate the feasibility of using the combustion noise acoustic output as a non-intrusive diagnostic of some details of the combustion process. Investigated were an open premixed turbulent jet flame and a gas turbine combustor converted to run on propane. The analysis links the acoustic pressure fluctuations to the distribution of heat release rate fluctuations. Measurement of the sound field, in principle, yields the heat release rate fluctuation field. It was found,

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however, that the analytical methods for this inverse problem are too sensitive to small experimental uncertainties. Consequently, it appears that the method is not, ~~feasible,~~ in general, feasible.

Summary

The purpose of this work was to investigate the feasibility of using the noise radiation from turbulent flames, such as in a gas turbine combustor, to a non-intrusive diagnostic tool. In particular, it was sought to non-intrusively measure the heat release rate spatial distribution by monitoring the acoustic output, in an appropriate manner.

Two experimental configurations were investigated. The first was an open, premixed turbulent flame burning in an anechoic chamber. Here the near pattern sound field was monitored. The second configuration was a gas turbine combustor, modified to burn on gaseous propane, where flush wall-mounted pressure transducers monitored the pressure fluctuations.

Analytically, there exists a relationship between the spectral sound output and the spectral content of the heat release rate fluctuation. The relationships are different in the two experimental configurations, but they exist. However, to obtain the heat release rate fluctuation, a difficult inverse problem must be solved. The result requires either a) inversion of an integral equation of the first kind or b) experimentally determining a second derivative in space of the fluctuating pressure. Both of these problems require extreme experimental accuracy.

Verification of the acoustic results was carried out by optical emissions (in the case of the open flame) and ionization measurements (for both flame types). The ionization measurements were made with intrusive probes, whereas the optical emission measurements were non-intrusive. In both cases there exists relationships between the signal measured and the heat release rate fluctuation.

For both flame types the spatial resolution was found to be insufficient to obtain pointwise heat release rate fluctuation spectra. The fundamental reason is that the sound wavelength was long compared with the integral scale of turbulence. Under certain circumstances it was found possible to measure the following quantity: the cross section average heat release rate spectrum times an axial correlation length scale of the turbulence. However, in the practical case of the gas turbine combustor, the inversion process was simply too sensitive to experimental errors to guarantee success on every configuration tested. It is concluded that this diagnostic tool is not feasible, in general.

Foreword

This work was performed as Contract No. DAAG-29-79-C-0087 from the U. S. Army Research Office. Dr. Robert Singleton was the initial contract monitor and during the last year of the program Dr. David Mann was the monitor. Dr. M. K. Ramachandra received his Ph.D. under this program, doing the open flame work. Mr. Yei-Chin Chao has performed the gas turbine work with the help of Mr. Deshang Fang. Mr. Chao will receive his Ph.D in December, 1983.

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Introduction

In all turbulent flames noise is radiated from the combustion region, and there is usually a range of frequencies where this noise is dominant over other flow noises. This noise is called direct combustion noise[1] and is of interest in its own right as a noise pollution problem. This program, however, asks the inverse question. Is it possible that appropriate sampling of the noise can tell something about the combustion process? Since the sampling of the pressure fluctuation field may be made nonintrusively, the acoustic radiation may be thought of as another diagnostic comparable with electromagnetic radiation. The issues are a) what does the noise measure about the combustion process, and b) is the measurement feasible?

For all flames the author has encountered an equation may be derived, under fairly weak approximation, that relates the sound field to the local heat release rate fluctuation. Specifically, if p_ω and Q_ω are the Fourier transforms of the acoustic pressure and heat release rate per unit volume, respectively, the general form of the equation is

$$\mathcal{L}(p_\omega) = - Q_\omega \tag{1}$$

Here $\mathcal{L}$ is some linear operator, depending on the particular configuration. Equation (1) may be used outright by measuring the left hand side, thereby measuring Q_ω. Alternatively, Eq. (1) can be solved through a Green's function, G, (sometimes analytical but in general numerical) to yield

$$p_\omega = \int_V G(\vec{r},\vec{r}_o)\, Q_\omega(\vec{r}_o)\, dV(\vec{r}_o) \tag{2}$$

where V is the volume where combustion occurs. Equation (2) is an integral equation of the first kind. In principle the left side of Eq. (2) may be measured and there are techniques to solve this integral equation for Q_ω.

What is fine in principle is not so in practice. The $\mathcal{L}$ operator is Eq. (1) is a differential operator of at least second order. Consequently, a second derivative measurement is called for, if Eq. (1) is used. If Eq. (2) is used it is well known that difficulties in inversion will occur. The problem here is that the integration process smooths out the integrand so that small errors in measurement of p_ω can translate into large errors into the deduced Q_ω. The two problems, with either Eq. (1) or Eq. (2), are actually equivalent; they are inescapable in this inverse problem.

These difficulties were known in advance. However, the attempt to use the acoustic radiation as a Q_ω diagnostic was considered desireable for several reasons. First, the acoustic radiation is not affected by optical opacity due to soot or smoke. Second, knowledge of the distribution of Q_ω would be useful as a diagnostic for pollution production, liner heat transfer and length requirements for complete combustion. Third, the acoustic measurement can be made nonintrusively. Consequently, the program attempted the measurements. One configuration was the test bed of the method -a simple premixed turbulent flame burning in an anechoic chamber. Some success here led to the practical configuration of an actual gas turbine combustor.

The simple flame work is now in the archival literature,[2] so that only the main results will be covered here. The gas turbine work has not yet been reported upon in the literature, so more detail will be given in this report.

Results

Premixed Turbulent Flame

The form of Eq. (1) used for the premixed propane-air jet flame burning in an anechoic chamber was

$$\nabla^2 p_\omega + k^2 p_\omega = -(\gamma - 1)\, i\omega\, Q_\omega \tag{3}$$

Here ω is radian frequency γ is the ratio of specific heats, k is the wavenumber, $\omega/\bar{c}$, $\bar{c}$ is the speed of sound in the free field surroundings, and $i = (-1)^{1/2}$. The form of the solution was as in Eq. (2) where the free space Green's function is

$$G(\underset{\rightarrow}{r}, \underset{\rightarrow}{r}_o) = \frac{e^{-ik|\underset{\rightarrow}{r} - \underset{\rightarrow}{r}_o|}}{4\pi|\underset{\rightarrow}{r} - \underset{\rightarrow}{r}_o|} \tag{4}$$

Near field microphone data were taken, as reported in Ref. (2) and auto-spectral densities were constructed through Fourier analysis. A fundamental problem was encountered in the inversion of Eq. (2) that the wavelength (≈ 1 ft) of sound was so long compared with the integral scale of turbulence that length details on this scale could not be discerned. As a consequence the quantity finally sought was

$$F \equiv \int_{-\infty}^{\infty} \hat{Q}_\omega(x_1)\, \hat{Q}_\omega^{*}(x_1 + \xi)\, d\xi \tag{5}$$

Here $\hat{Q}_\omega$ is the cross section average of Q_ω and ξ is a space separation distance. F may be viewed as an autospectrum of $\hat{Q}$ times an integral length scale of the turbulence.

Inversion of the integral equation was carried out, with difficulty, using an augmented Galerkin method.[3] Verification of the results was carried out by C_2 radical emission studies[2] and ionization measurements.[4] Good agreement was found between all methods, but there was one important qualifier with the acoustical method. That was that the <u>empirical visual flame length had to be input to the computer</u> for the inversion method to give good results. That is, if the experiment and inversion method were asked to yield the flame length, poor results were obtained. Since this was part of the information sought for practical application of the method, some trouble was anticipated in the gas turbine application. Nevertheless, the partial success led to an attempt at the gas turbine problem.

Gas Turbine Application

Facility

The facility used was a modified version of a gas turbine combustor facility described in Ref. (5). The combustor is shown in Fig. 1. The combustor was modified to burn gaseous propane by construction of three different injectors of the general form shown in Figs. 2 and 3. For later designation, DS refers to diffusion injector with a short flame, DM refers to a diffusion injector with a medium length flame, PS refers to a premix injector with a short flame and PM follows with a similar designation. For verification of results, a cross-section averaging ionization detector was used as shown in Fig. 4. Wall acoustic pressures were taken with water cooled pressure transducers, five at a time, mounted in any of seventeen

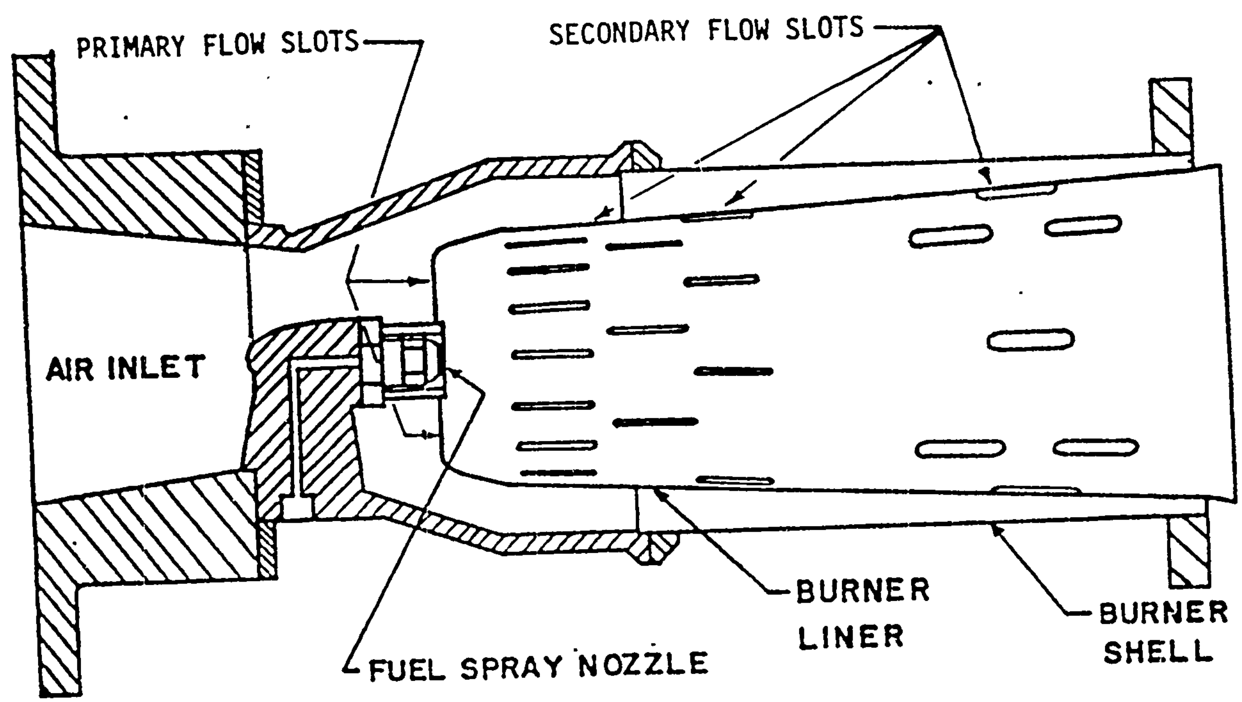

Figure 1. Combustor schematic.

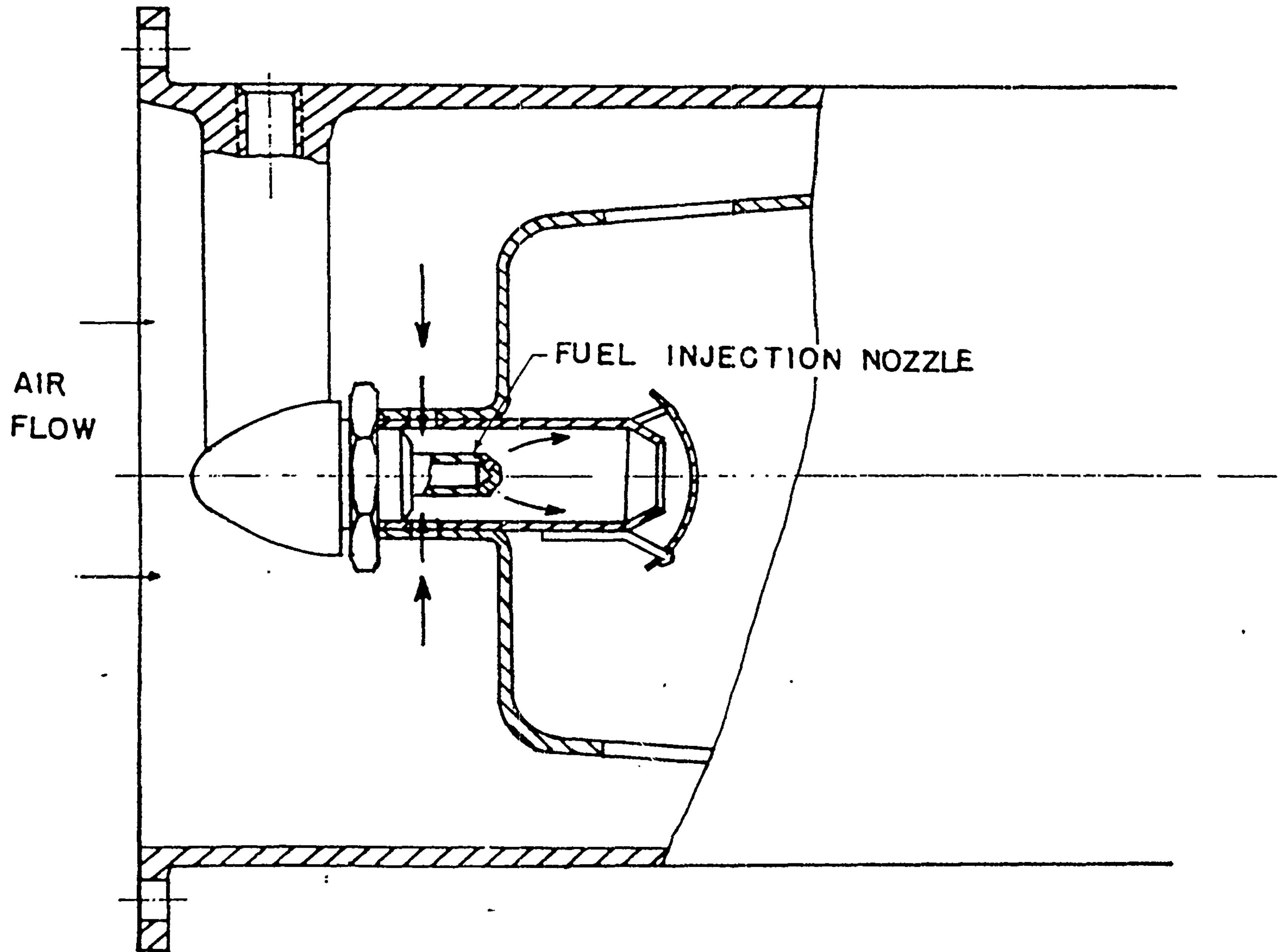

Figure 2. Short flame, partial premix injector.

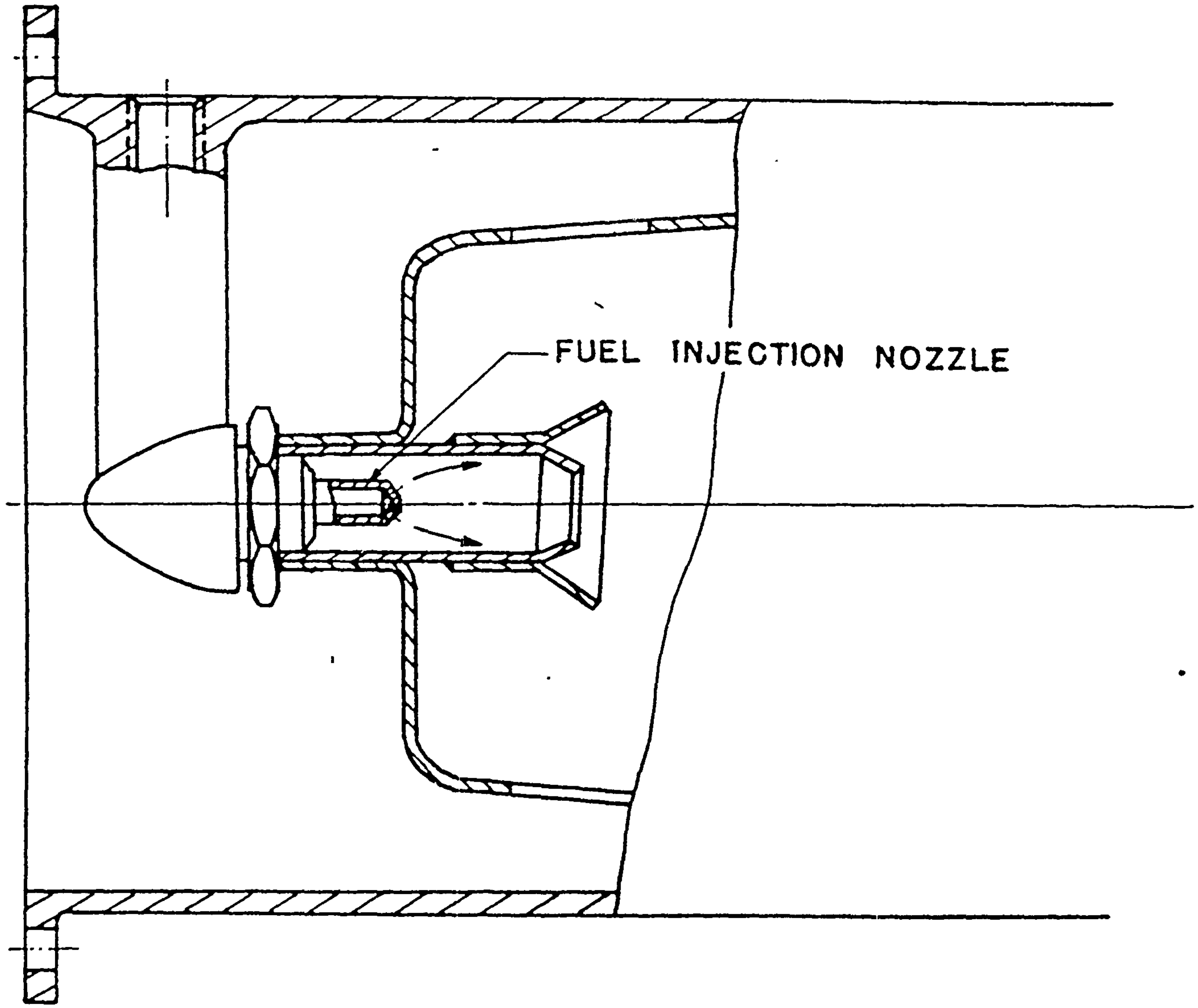

Figure 3. Long flame, no premix injector.

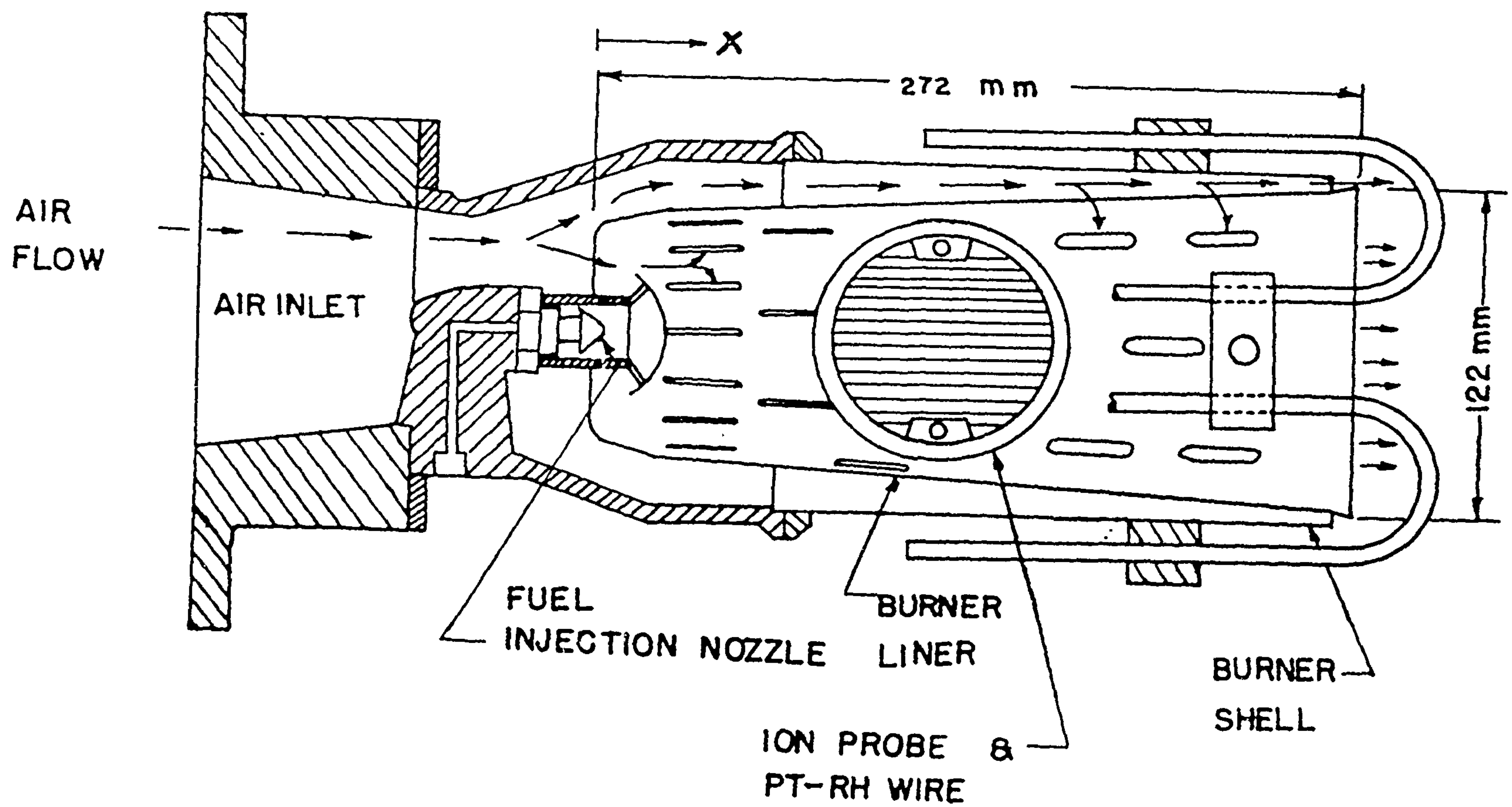

Figure 4. Cutaway view of combustor and schematic of ionization probe.

access holes shown in Fig. 5. Since it was found necessary to measure the axial speed of sound distribution in the combustion chamber, a pulse technique was developed, as shown in Fig. 6, and this was verified by thermocouple measurements. A typical comparison of the cross-section average speed of sound as obtained by the two methods is shown in Fig. 7.

Analysis

The equivalent of Eq. (1) for the gas turbine combustor is

$$\frac{d}{dx}\,\bar{c}^{-2}\,\frac{d\eta_\omega}{dx} + \frac{1}{A}\,\bar{c}^{-2}\,\frac{dA}{dx}\,\frac{d\eta_\omega}{dx} + \eta_\omega\left[\omega^2 - i\omega\,\frac{C}{A}\,\frac{\bar{c}}{\xi}\right] = -\,i\omega(\gamma-1)\,\frac{\hat{Q}_\omega}{\bar{p}} \qquad (6)$$

This is the plane wave version of the acoustic problem since experimentally all of the combustion noise spectral content lies at frequencies well below the cut-on frequency of the first transverse mode. New symbols appearing in Eq. (6) are $\eta_\omega \equiv p_\omega/\bar{p}$ with $\bar{p}$ the mean operating pressure, A is the combustor cross section area, C is the circumference and ξ is the wall liner impedance defined by $\xi = p_\omega/u_{n_\omega})_{wall}$ and u_{n_ω} is the Fourier transform of the velocity component normal to the wall. This impedance is taken from a prior program[5] to be approximately 0.06.

Several methods were looked at in order to put Eq. (6) into a form for experimental determination of Q_ω. These included an integral equation formulation with numerical determination of the Green's function for the problem and direct measurement of the left hand side of Eq. (6). As in the open flame problem the determination of $\hat{Q}_\omega$ was found extremely sensitive

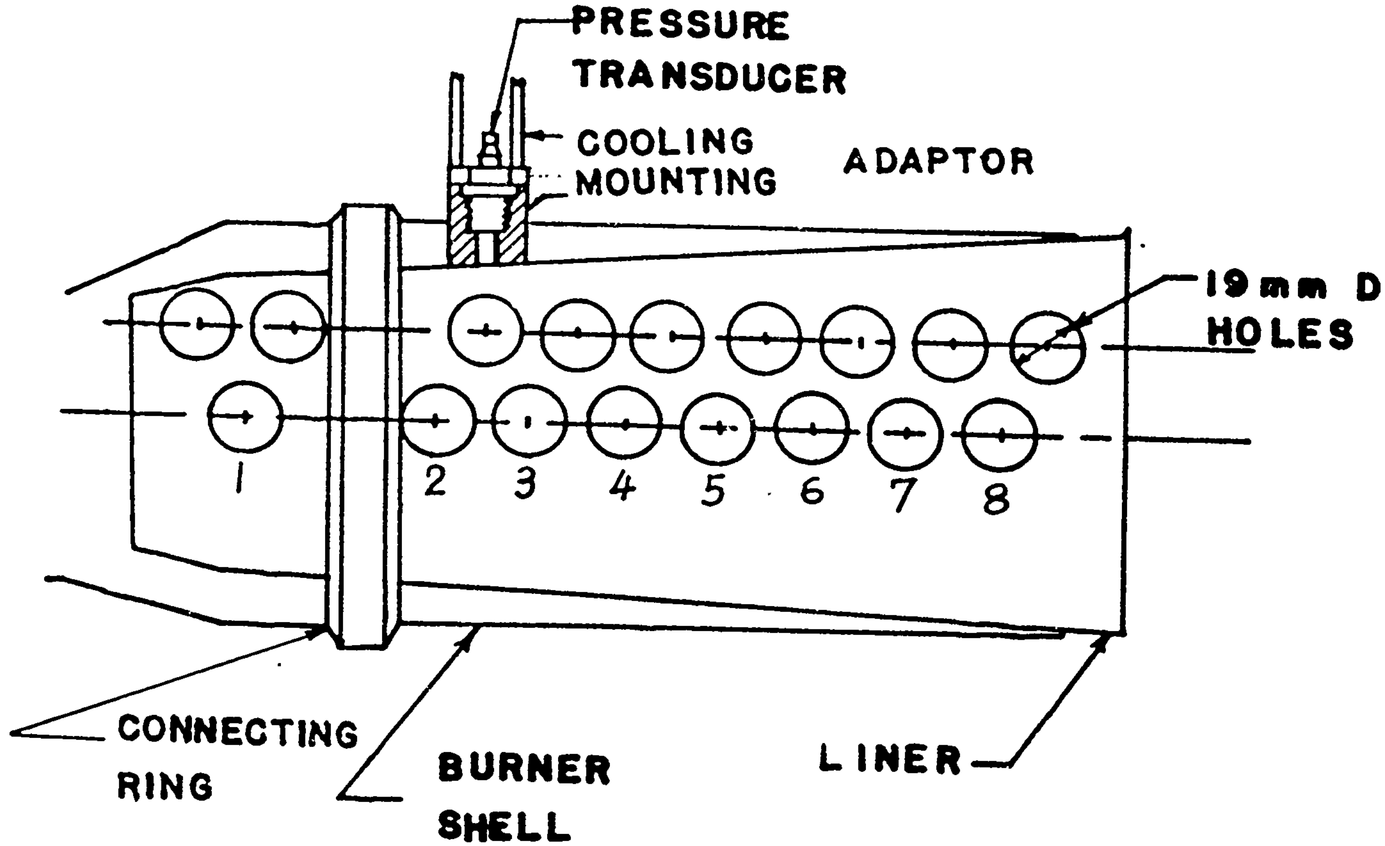

Figure 5. Sites for acoustic measurem_nt.

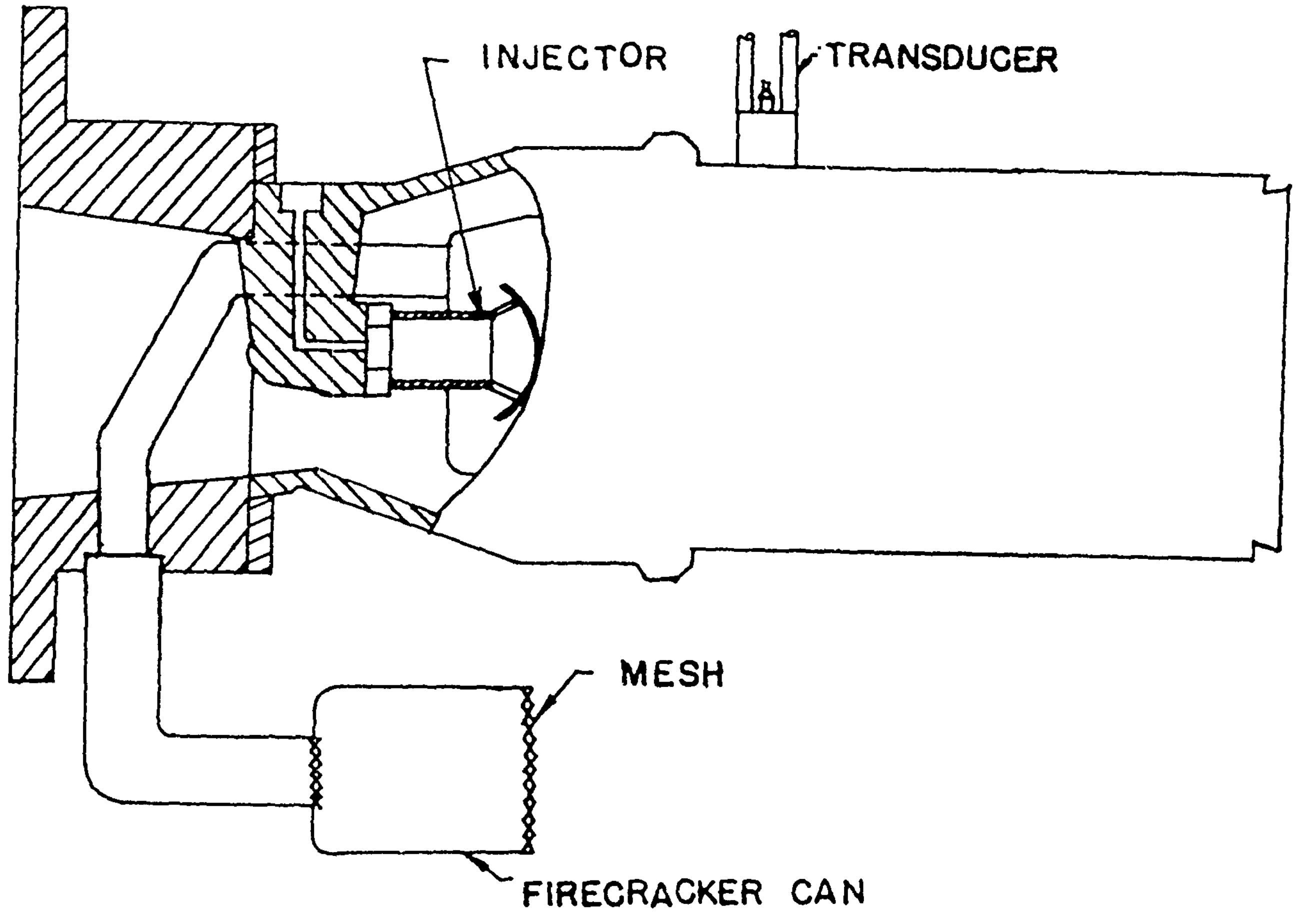

Figure 6. Setups for the pulse technique speed of sound measurement.

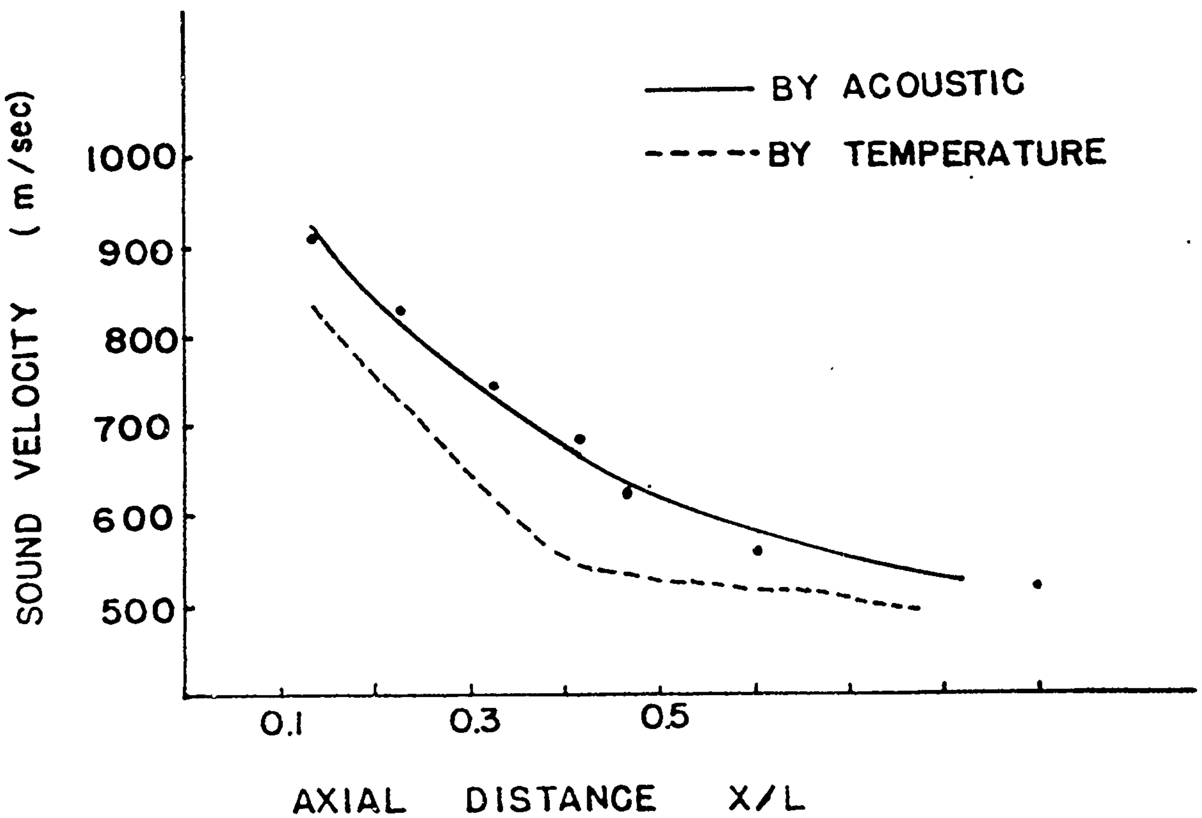

Figure 7. Comparison of speed of sound obtained from pulse technique and temperature measurements.

to experimental errors in measurement of η_ω. An empirical fact, however, aided in the choice of method. Two space-separated ion probes showed a rapid drop in coherence with only short space separation as shown in Fig. 8. This means that the axial correlation length scale is short compared with the combustor length, as was found in the open flame problem as well. Consequently, consider the solution of Eq. (6) in the form of Eq. (2) and consider this solution multiplied by the right hand side of Eq. (6)

$$\eta_\omega(x_1)\ \rho\left[-i\omega\ \frac{(\gamma-1)}{\bar{p}}\ Q_\omega^{\ *}(x_2)\right] = \frac{\omega^2(\gamma-1)^2}{\bar{p}^2}\int_0^{\ell} G(x_2,x_1)\ Q_\omega^{\ *}(x_2)Q_\omega(x_1)dx_2$$

$$\approx \frac{\omega^2(\gamma-1)^2}{\bar{p}^2}\ G(x_1,x_1)\ F \qquad (7)$$

where F has exactly the same meaning as in Eq. (5) for the open flame problem. If the left hand side of Eq. (6) is also multiplied by $\eta_\omega^*(x_1)$ and Eq. (6) is discretized, the left hand side consists of cross spectral densities of $\eta_\omega(x_1)$ and $\eta_\omega^{\ *}(x_i)$ where the x_i are the descretization points. Hence F is determined by measurements of the necessary cross spectral densities, if the Green's function may be computed.

As seen in Eq. (6) the distribution of c is needed, and that was the reason for the acoustic pulse test mentioned earlier. Also needed for construction of the Green's function are the acoustic impedance relations at the head end and open end of the combustor. That is, α is needed in

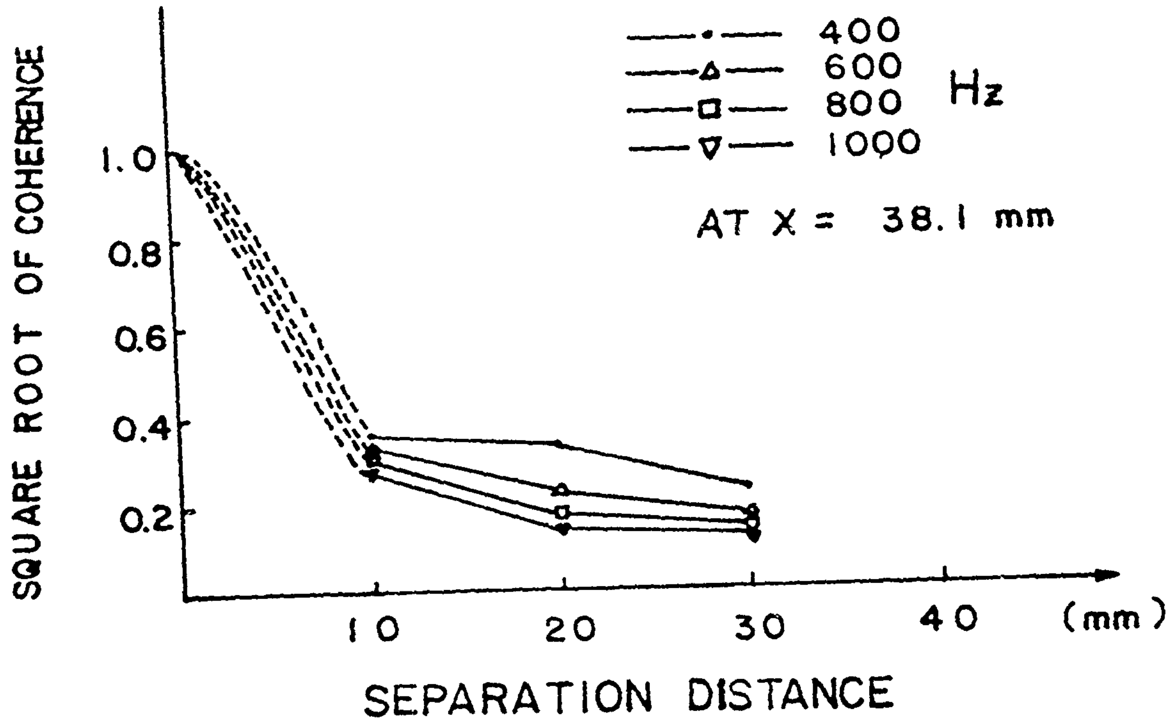

Figure 8. Square root of coherence of two space separated ion signals.

relations of the form

$$\frac{d\,\eta_\omega}{dx} + \alpha\,\eta_\omega = 0 \left.\vphantom{\frac{d}{dx}}\right\} \begin{matrix}\text{head}\\ \text{tail}\end{matrix}$$

These relations are discretized and multiplied by $\eta_\omega^*(x_2)$ to obtain

$$\frac{\eta_\omega(x_1)\,\eta_\omega^*(x_2) - \eta_\omega(x_2)\,\eta_\omega^*(x_2)}{\Delta X} + \alpha\,\eta_\omega^*(x_2)\eta_\omega(x_1) = 0$$

The necessary spectral densities are measured and α is computed.

Experiments

First consider some ion density measurements for a particular run in Fig. 9. The number following the injector specification refers to the pressure drop across the air metering orifice. A larger number indicates larger airflow rate. Shown are the mean and rms values of the local, cross-section averaged ion densities. The major point is that in all cases there is a general correspondence between the two. That is, the fluctuating rms gives a good indicator of the mean. The mean is what is really wanted, but acoustic measurements can only determine the fluctuating quantity. Consequently, it was imperative that this check came out positively. There were three injectors run at two fuel/air ratios each. In all cases there was good agreement between the mean and rms ion curve shapes.

Consider now a selected set of pressure spectra in Fig. 10. Typically the combustion noise dominates the cold flow noise (and always dominates

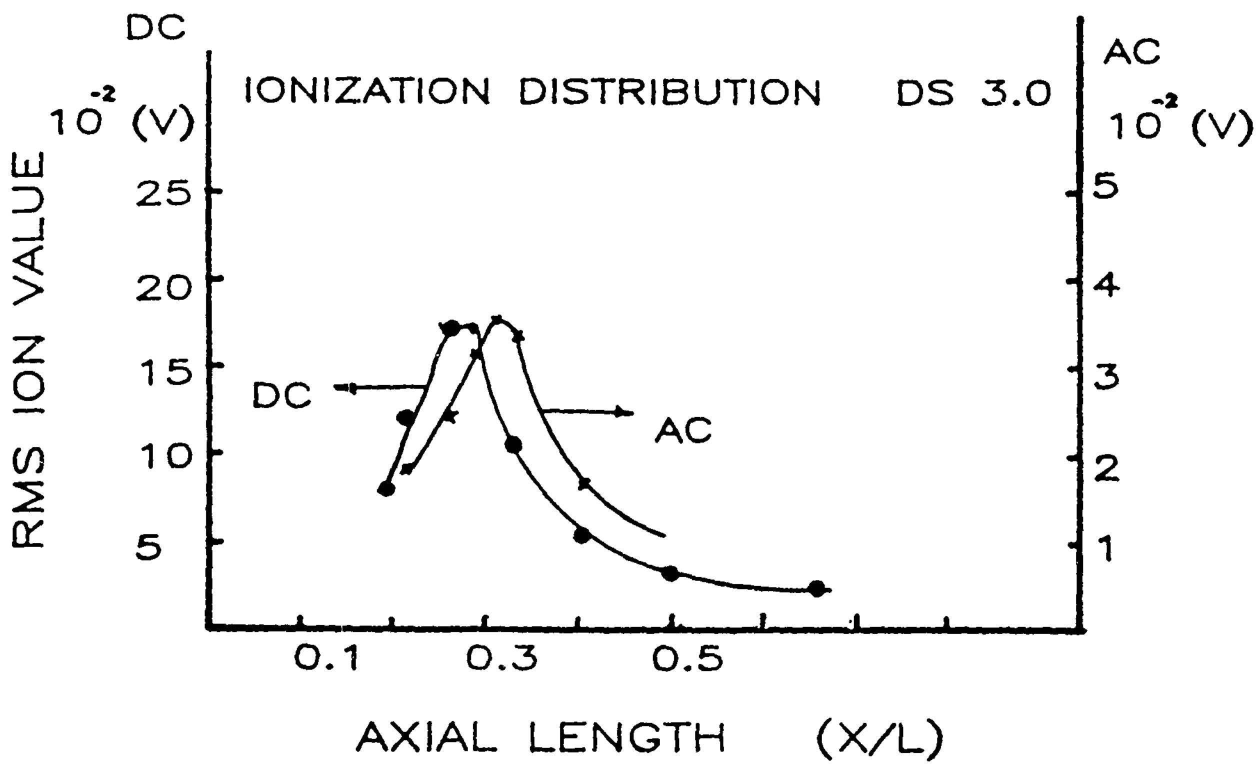

Figure 9. DC and AC ionization concentration distribution.

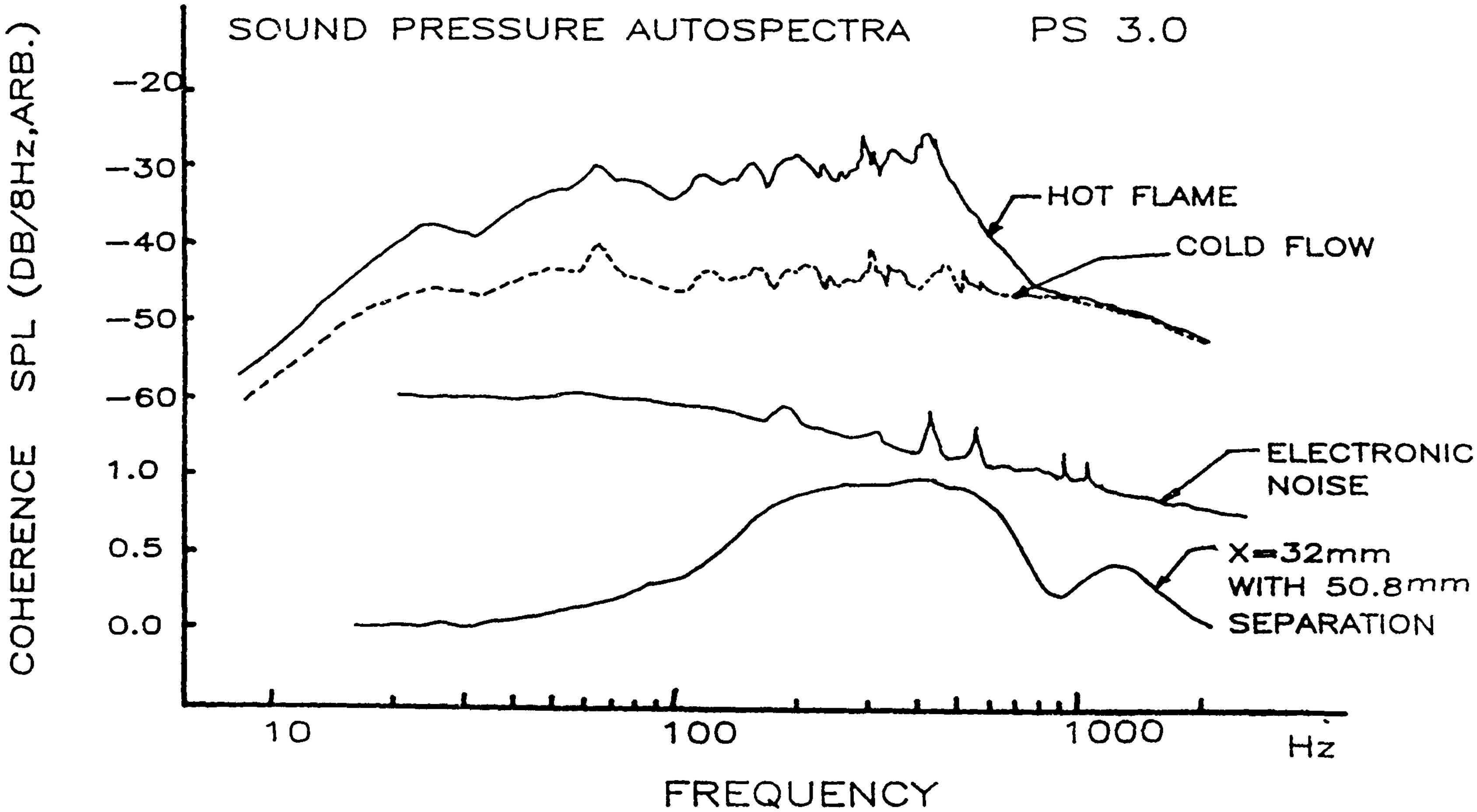

Figure 10. Typical combustion noise and cold flow noise autospectra and the coherence functions between two space-separated pressure transducers.

the electronic noise) until frequencies of the order of 900 Hz. That this combustion noise is propagational in character is shown by the coherence between two space-separated transducers. In the frequency regime between, say, 200 Hz and 700 Hz the high coherence indicates a causal, fixed phase relation between the two transducers, which is the property of an acoustic motion. The frequency range of use can be extended by using only cross-spectra as shown in Fig. 11. However, in measurement of the boundary conditions or for at least one location of pressure measurement it was found convenient to use at least one autospectrum in the data reduction. Consequently, only the frequency regime where the combustion noise autospectra were dominant were used.

A typical generation of cross spectra between point x and a reference point R (S_{XR}) is shown in Fig. 12. These cross spectra, of course, have phase and magnitude. In this regard the Green's function in Eq. (7) has both phase and magnitude. But F has been constructed to be real and positive. Consequently, a first test from the experiment is to see if F is, in fact, real and positive.

A typical result for the short flame premixed injector is shown in Fig. 13. The solid curves are the ratio of F_{real} to its maximum value; the dashed lines are the imaginary part of F. Clearly, the method fails the first test. The imaginary part is not negligible compared with the real part. However, the second test, that the real part is generally positive, is in fact passed. The procedure chosen from here on is to accept the imaginary part problem and simply ignore it; only the real part of F is retained.

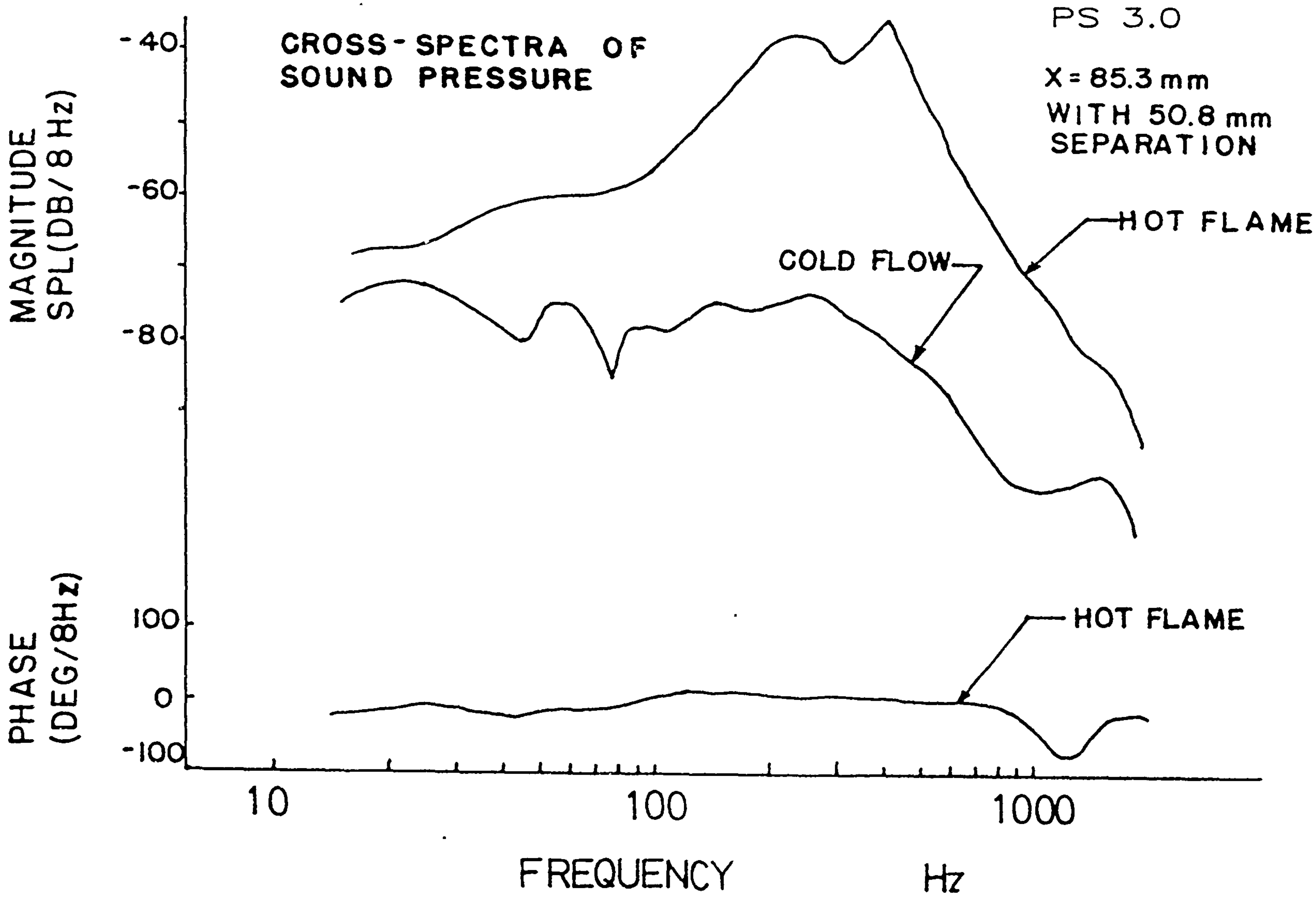

Figure 11. Typical combustion noise and cold flow noise cross-spectra.

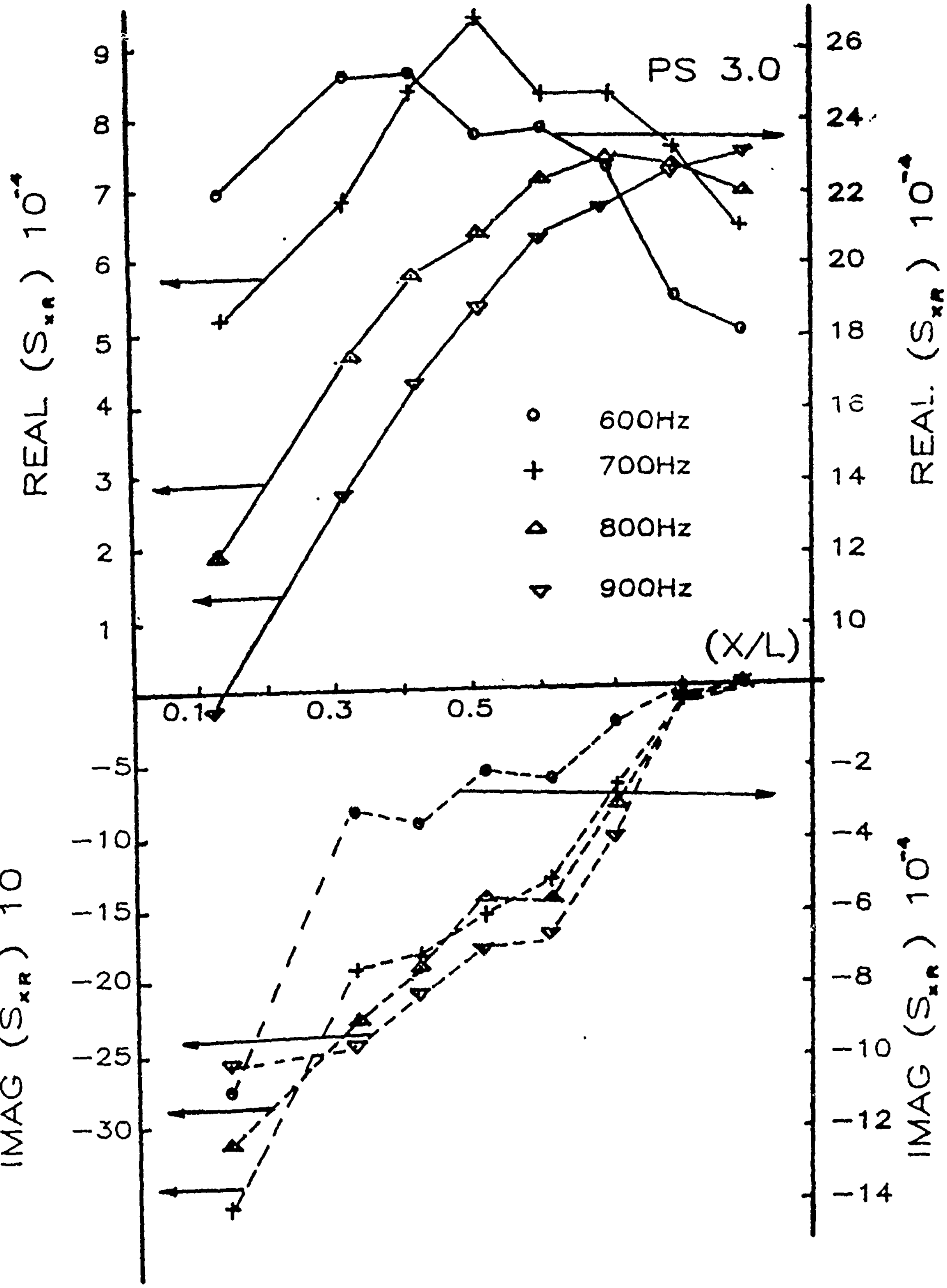

Figure 12. Typical axial variation of cross spectra between position x and a fixed reference microphone.

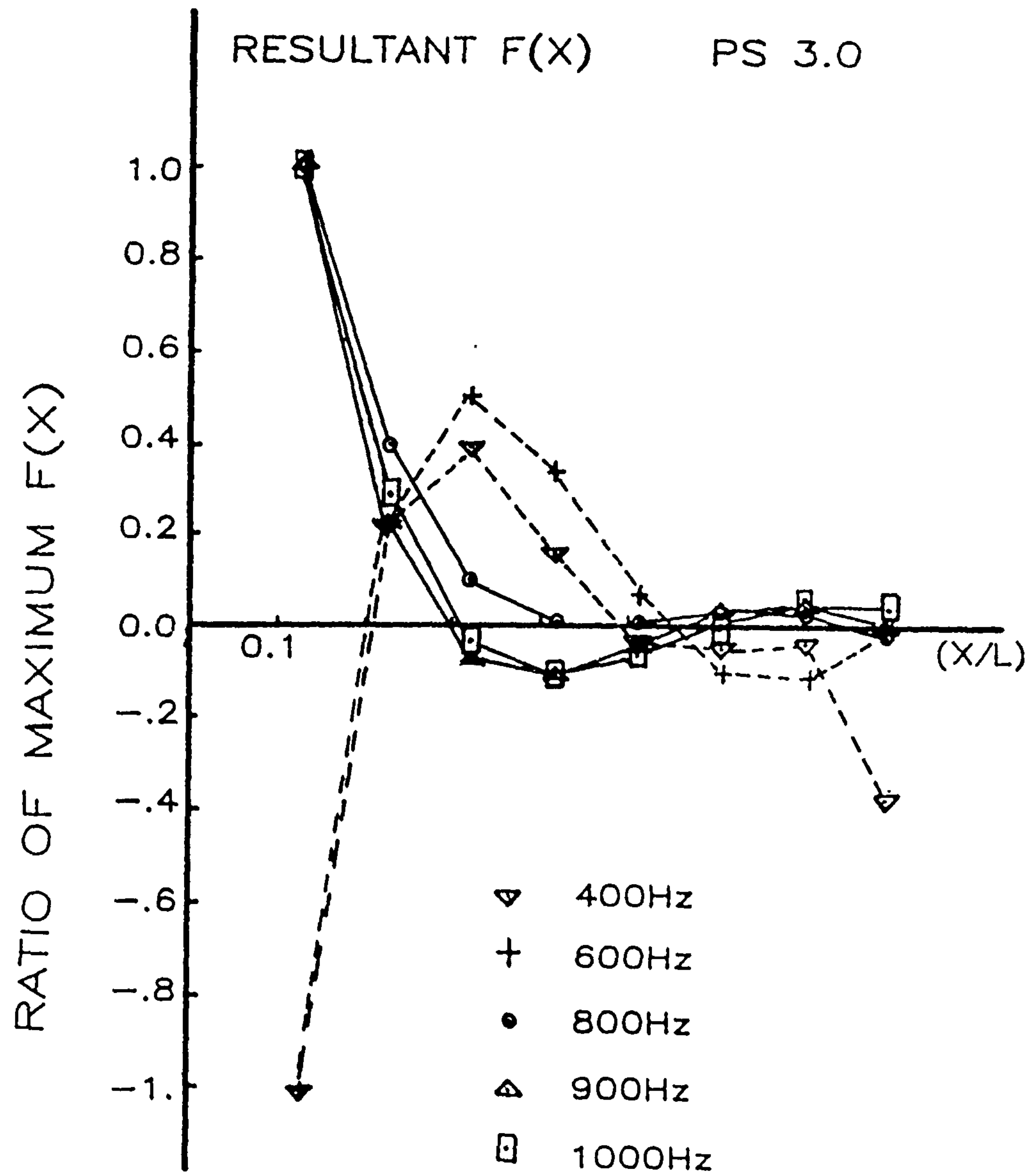

Figure 13. Real and imaginary parts of F deduced from acoustic measurements.

In Figs. 14 and 15 are shown the main successes for all four runs. It was always found possible to select a frequency band for the acoustic measurement for which F_{real} matched the shape of the ion AC measurement. However, the method never worked for all frequency bands. Shown in these figures is that 800 Hz appears good for all cases. However, there are no grounds to suspect that 800 Hz is a number good for the general case and for other combustors.

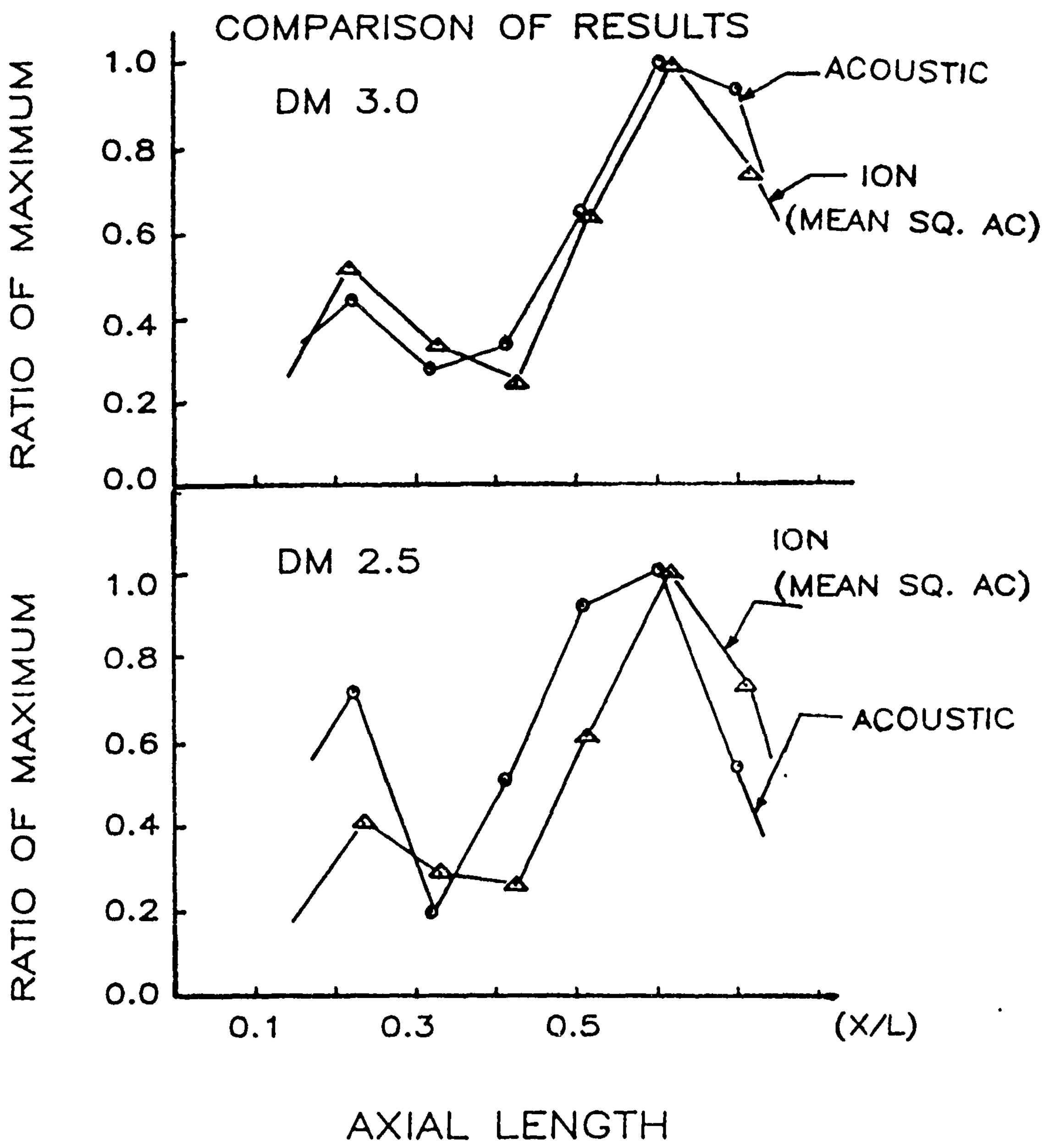

Figure 14. Comparison of F obtained by the acoustic method at 800 Hz with the mean square ionization distribution for two test cases.

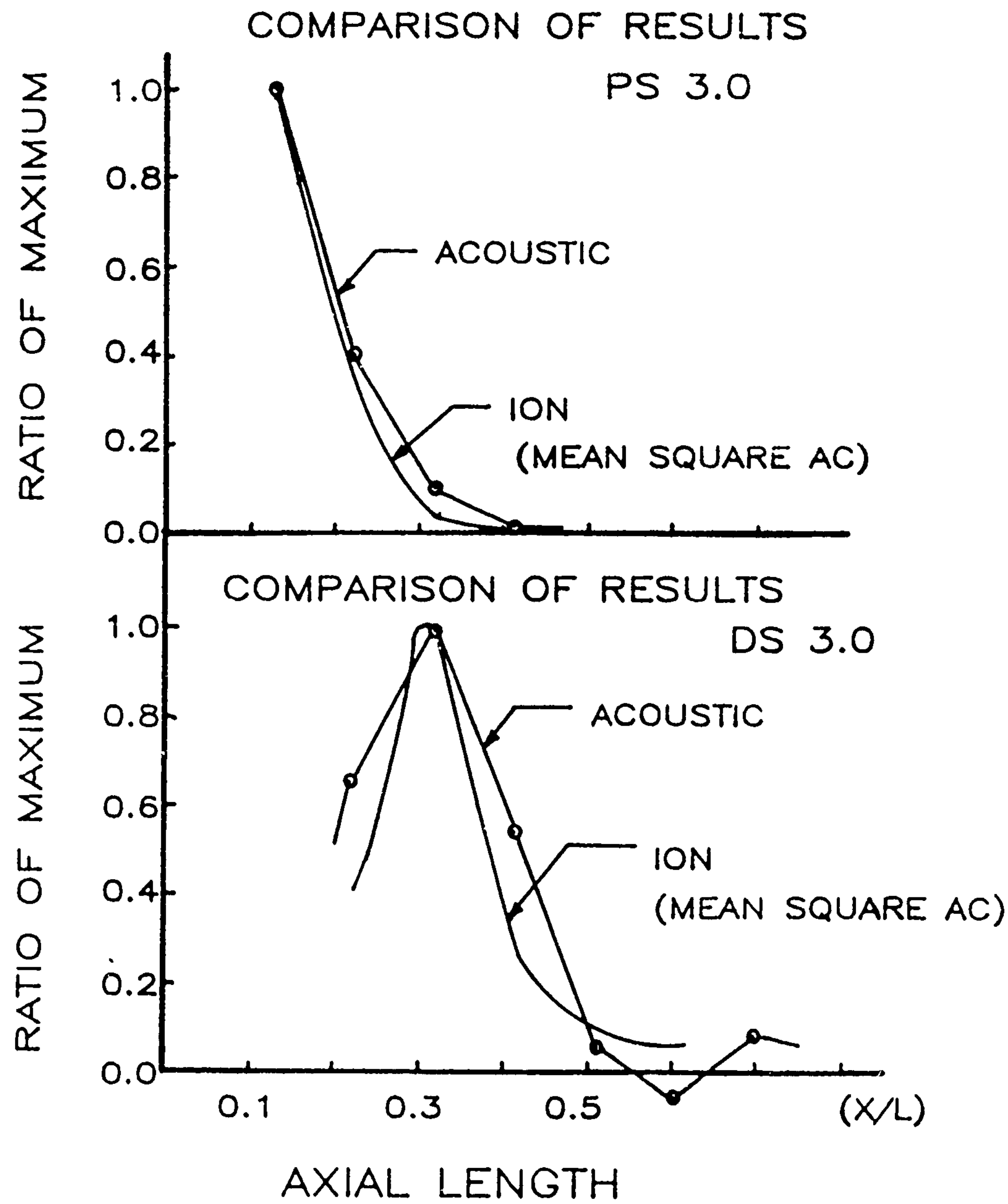

Figure 15. Comparison of F obtained by the acoustic method at 800 Hz with the mean square ionization distribution for two test cases.

Conclusions

Use of the acoustic method for diagnosing the heat release rate distribution in both a laboratory flame and a gas turbine combustor has met with limited success. There are two fundamental problems. First, combustion noise wavelengths are so long that small length scale information is very difficult to extract. Secondly, the inversion method for this inverse problem is known to be highly sensitive to small experimental uncertainty. The method gave reasonably good results for the open flame but substantial input (the flame length) had to be given a priori to the calculation. The gas turbine combustor results had to be heavily selected in order to provide good comparison of theory with experiment. It is concluded that it is not feasible to use this technique as a general developmental tool.

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